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RESEARCH MEMORANDUM

NOTES ON THE APPLICATION OF AIRFOIL STUDIES TO HELICOPTER ROTOR DESIGN

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SUMMARY

In order to facilitate the application of miscellaneous airfoil data to the problems of the helicopter designer, a discussion of a number of the problems most frequently arising is presented. A reference list of published reports on airfoil section characteristics (or their application) which experience has shown to be useful in connection with these helicopter problems is included.

INTRODUCTION

In order to arrive at a satisfactory design, the helicopter manufacturer must have accurate and detailed information on the basic aerodynamic characteristics of the airfoil which he selects for the rotor blades and on the effect of various operating conditions and practical modifications on these basic characteristics. Although a vast amount of applicable information has been published, most of it is not specifically aimed at helicopter problems, and the locating and digesting of the most suitable references have been found to represent a time-consuming search even when all of the reports on airfoils are already available for examination.

Recent discussions with helicopter designers have indicated that in relation to a number of specific airfoil problems the most suitable reports have frequently not come to their attention, as might be expected from the preceding considerations.

As a partial remedy for this situation, this paper presents a discussion of a number of such problems which are known to be of current interest. A reference list is included which consists of papers which have been found to be of particular assistance in helicopter research and design studies. This reference list is arranged in outline form so that it can be used as a series of bibliographies, with headings similar to those used in the discussion. Where appropriate, the same papers are listed under more than one heading. Neither the discussion nor the reference list is exhaustive in coverage, but they are expected to provide a starting point from which detailed studies may more readily proceed.

DISCUSSION

I. Aerodynamic Characteristics

References 1 to 11 provide the basic aerodynamic characteristics of most, if not all, of the NACA airfoil sections of interest to helicopter designers. Reference 1 is a summary report which effectively takes the place of numerous individual reports on the aerodynamic characteristics (including lift, drag, moment coefficient, and aerodynamic center values) of NACA 4-digit, NACA 5-digit, and NACA low-drag sections. Cross-plots are included in this reference which show the effect of systematic changes in factors such as thickness and camber on minimum drag and maximum lift coefficient.

NACA 4-digit and 5-digit airfoils.- Of the NACA 4-digit series, the symmetrical sections (particularly, the NACA 0012) have seemed of most interest to helicopter designers, the symmetrical section being considered advantageous in respect to ease of construction and zero pitching-moment coefficient. The 5-digit series achieves extremely low pitching-moment coefficients together with positive design lift coefficients by placing the maximum camber far forward. This series has the same thickness distribution as the 4-digit airfoils. Of this family, the NACA 23000 series (for example, the NACA 23012) has usually appeared to be the best all-around choice and has been used in a number of successful designs.

NACA low-drag airfoils (other than special helicopter sections).- Most of the low-drag airfoils which have been developed (references 4 and 5) have too high a pitching-moment coefficient to warrant consideration for use with current helicopter designs. The symmetrical sections are not promising since half of the low-drag "bucket" or, in other words, half of the limited range of lift coefficients over which the important drag reductions are achieved is below zero lift; whereas the faster-moving portions of the helicopter blade are nearly always operating at positive lift coefficients. A few of these sections (such as the NACA 64-110, with relatively low camber; see reference 4) may be of interest for helicopter designs wherein low mean lift coefficients and low tip-speed ratios are used, as is the case with some jet helicopter designs.

Special helicopter sections.- In order to place the low-drag bucket in a useful range of lift coefficients and still retain zero or almost zero moment coefficient, a number of special airfoils (see references 6 and 7) have been derived. On the basis of section data obtained from two-dimensional wind-tunnel tests, together with theoretical calculations, the NACA 8-H-12 and NACA 9-H-12 airfoils appear more promising for use as rotor-blade sections, from an aerodynamic point of view, than any other airfoils thus far tested at the NACA Laboratories. Section data for high Mach numbers are still lacking, however, and these airfoils have not yet been tested in actual rotors. The applicability of section data to the actual rotor, in which the boundary layer is subject to centrifugal action and the airfoil is subjected to rapid variations in speed, angle of attack, and yaw angle, is considered to be far more conjectural with these special sections than with the NACA 4-digit or 5-digit airfoils, pending tests of the special airfoils in actual rotors.

Section characteristics at angles of attack beyond the stall.- The calculation of rotor forces requires the estimation of forces on the airfoil at angles above that for stalling, in fact, through a full 360° angle-of-attack range. References 8 to 11 will not provide much precise information for modern airfoils, but fortunately these high angles occur only in regions of the rotor disk where the relative airspeed is low. Consequently, rough estimates rather than precise values are usually adequate.

II. Effects of Various Parameters on the Aerodynamic Characteristics

Reynolds number.- Most of the information on section characteristics which has been obtained in modern low-turbulence wind tunnels has emphasized Reynolds numbers higher than those encountered with a typical helicopter rotor. Reference 12 does much to fill this gap, providing data for the NACA 23012, for example, in both the smooth and standard roughness conditions over the range of Reynolds numbers of most interest for current helicopter designs. References 13 to 18 contain further information on effects of Reynolds number.

Mach number.- References 19 to 28 cover theoretical and experimental treatments of the effects of compressibility on airfoil characteristics. In applying theoretical values of critical Mach number (such as those given in references 19 and 20) to the prediction of Mach numbers for force breaks, it should be remembered that the increment between the critical value and that for the force break will vary with angle of attack and also with the type of section. Information on this point will be found in most of the references given for effects of compressibility.

A further consideration in applying data on critical Mach number to the helicopter rotor is that an allowance apparently should be made for "tip relief." Study of results of efficiency tests on numerous propellers indicates that losses due to compressibility are not measurable until the tip Mach number is about 0.06 higher than would be calculated from the measured section data.

In choosing a section for operation at high Mach numbers and low angles of attack, the NACA 0000-64 series sections, test results for which are given in reference 24, should not be overlooked. (See reference 3 for low-speed aerodynamic characteristics.) These sections may be found to be more advantageous structurally, for some current types of blade construction, than many of the newer low-drag sections.

These airfoils differ from the familiar 4-digit series only in that the point of maximum thickness is moved from 30 percent to 40 percent chord, but they nevertheless realize appreciably higher critical Mach numbers.

In relation to the choice of airfoils for operation at high Mach numbers and high angles of attack, it may be remarked that examination of available test data on compressibility effects indicates that at Mach numbers near the critical value, the NACA 23000 series has lower drag at angles of attack approaching that for maximum lift coefficient $C_{L_{max}}$ and has a higher value of $C_{L_{max}}$ than the NACA 4-digit series. Little difference is noted for low angles of attack.

In studying the effect of airfoil thickness on critical Mach numbers, the predicted values of reference 19 may be supplemented to advantage by experimental data given in references 22 to 24.

Greater emphasis has recently been placed on designing the aft portion of the rotor blade to withstand the loads occurring at high Mach numbers. The pressure-distribution data of reference 21 should be interesting in this connection.

Surface condition.- Information which is useful in evaluating the changes in airfoil characteristics caused by imperfections in the rotor-blade surface may be found in references 29 to 35. It is now well known that the profile-drag- and maximum-lift-coefficient data discussed in part I will not apply unless the rotor-blade surface is sufficiently smooth and free from errors in contour. In some cases, however, the blade construction is made unnecessarily expensive, while still not achieving the desired end, by requiring extremely close dimensional tolerances and a mirror-like finish without providing a check on local waves, ridges, or other lack of fairness. Apparently the straightedge test (described in reference 29) is still the best practical starting point for checking local contour errors. The surface need not be polished to a mirror finish after painting but should be sanded free of specks, as discussed in reference 30.

Drag measurements on practical-construction specimens (see references 31 and 32) show that with certain types of helicopter blade construction which have been rather extensively employed in the past profile-drag coefficients which are 50 percent or more above the values for the basic section may result from various combinations of contour errors, surface roughness, and deformation under load. Results given in reference 31 (for NACA 4-digit-series airfoils) also show that most of this 50-percent increase in profile drag can be avoided by use of other available types of construction. It should be pointed out, however, that the effects of deterioration with time and use were not investigated. The results reported for practical-construction specimens of airplane wings in reference 32 suggest that further improvement may be obtained by means of types of construction which, particularly as applied to rotor blades, are still in the experimental stage.

Both contour errors and roughness are far more critical, as regards drag increase, in the region ahead of the point of minimum pressure than behind it. This consideration results from the fact that the transition from laminar to turbulent flow tends to occur near the point of minimum pressure for a perfectly smooth airfoil, so that imperfections ahead of the point of minimum pressure, but not behind it, may cause considerable forward shift of the transition point. The points of minimum pressure for the various airfoils are given in many of the references discussed in part I. An unusually complete treatment is given in reference 29.

It should not be inferred from the preceding discussion that the effects of roughness behind the point of minimum pressure, or aft of the transition point, are negligible. Reference 33 shows an increase of about 15 percent in profile drag due to roughening the airfoil behind the transition point.

Both small errors in leading-edge radius and small amounts of leading-edge roughness can produce significant reductions in maximum lift coefficient, making the leading-edge portion the critical one in this respect.

Large amounts of surface waviness can cause the drag rise due to compressibility to occur at a lower Mach number (see references 34 and 35).

Surface waviness and roughness are in general not expected to have much effect on either the moment coefficient or the aerodynamic center, except that waves right at the trailing edge can produce changes in camber or in thickness distribution. The effect of these trailing-edge errors (or modifications) will be discussed next.

Effect of trailing-edge modifications on moment-coefficient values.- It is well known that the moment coefficient (and, hence, the center of pressure) is sensitive to changes in camber near the trailing edge. For example, data on an airfoil equipped with a 20-percent-chord plain flap given in reference 36 indicate that a moment-coefficient increment of 0.01 will result from a change of 1.2° in the flap setting. For a typical rotor blade this change in flap angle is equivalent to about 0.05-inch deflection of the trailing edge relative to the airfoil-chord line. Smaller flap chords result in still greater sensitivity in terms of inches at the trailing edge. For example, a 10-percent-chord flap has been estimated to require only about 0.03-inch deflection as compared with 0.05 for the 20-percent-chord flap, for the same change in moment coefficient. Since a moment-coefficient change of 0.01 is generally considered significant by the helicopter designer, it will be apparent that small construction errors can cause significant deviations from the published moment-coefficient values. Conversely, any small adjustments desired in the moment coefficient can be achieved by extremely small deflections of the trailing edge.

Effect of trailing-edge modifications on aerodynamic-center values.- Evidence is sometimes reported of differences between the aerodynamic center on an actual rotor blade and that given by wind-tunnel tests. Examination of the problem suggests that construction errors, or distortion under load, affecting the thickness distribution near the rotor-blade trailing edge may account for most if not all of these apparent discrepancies, even if the mean-line camber is accurate. Thickening the rear portion of the airfoil tends to move the aerodynamic center (and, hence, the center of pressure) forward, and vice-versa. The importance of small changes in thickness distribution near the trailing edge is illustrated by the results reported for various internal pressures (with a fabric-covered blade) in reference 37 and by the data of reference 38. It may also be noted that airfoils designed with a cusp-type (concave) trailing edge have been found to have aerodynamic-center positions farther aft than those designed with thick (bulged or convex) aft portions; for example, see figure 21 of reference 39.

Effect of trailing-edge modifications on drag.- The effect on drag of several trailing-edge modifications is given in references 38 and 40. The effect of much larger modifications than are covered in these references becomes of interest in connection with jet-powered rotors, perhaps the simplest case being the cutting off of the trailing edge of the airfoils to accommodate the jet. In this connection, study of available information yields several items of interest. With the jet operating, and below the critical Mach number, the drag chargeable to the airfoil seems likely to be of the same order as for the basic section (with no cut-off), that is, skin friction and not form drag. The Mach number for the drag rise will probably not be affected appreciably by the jet. With the jet inoperative, and below the critical Mach number, any cut-off large enough to accommodate a jet appears likely to increase the section minimum profile-drag coefficient to several times the value for the unmodified section. The Mach number for the drag rise apparently is not appreciably affected by cutting off the trailing edge (see references 41 and 42).

Effect of trailing-edge modification on lift.- The effect of a number of trailing-edge modifications on the angle of attack for zero lift is shown in references 36 to 40. As would be anticipated, significant effects are in general shown only for changes in trailing-edge camber.

The effect of several trailing-edge modifications on the slope of the lift curve may be found in references 37 to 39. In this connection it may be noted that cusp-type (concave) trailing-edge shapes result in appreciably higher lift-curve slopes than plain or bulged trailing-edge shapes. (See fig. 19 of reference 39.)

The effect of trailing-edge camber-line changes on the maximum lift coefficient may be estimated by means of the data for plain flaps given in reference 36, and some indication of the effect of several other modifications may be obtained from references 37 and 38.

III. Application of Airfoil Section Data to Prediction of Rotor Characteristics

Theoretical treatments.- Means for computing rotor characteristics (including lift, drag, shaft torque, and blade motion) from known or assumed airfoil section characteristics are provided in references 43 to 45. Reference 43 provides means for computing rotor forces and rotor-blade motion for any fixed lift-curve slope and for any drag polar which can be represented by a three-term power series. Reference 44 provides a much quicker solution for rotor lift, drag, and torque values, particularly for power-on helicopter operation. This simplification is achieved by providing charts based on a specific airfoil-section lift-curve slope and likewise based on a specific drag polar which is considered reasonably representative of the contour accuracy and surface smoothness achieved with carefully built rotor blades. Reference 45 provides a method of calculation of rotor profile-drag power losses applicable to airfoils having irregularly shaped drag polars which cannot be represented by a three-term power series. In addition to examples illustrating the effect on rotor power losses of changes in the airfoil drag polar, an examination of the variation of conditions of operation (such as Reynolds number and yaw angle) to which the airfoil is subjected by use in the rotor is included.

Experimental verification.- Because of the complexity of the actual conditions of operation just mentioned, experimental checks of the applicability of section characteristics to prediction of rotor characteristics are required. Such checks have been presented in references 46 to 52. References 46 and 47 are of particular interest in that the profile-drag power losses calculated from the charts of reference 44 are shown to be in reasonable agreement with the experimental values except for conditions where stalling of the retreating blade is encountered. These stalled conditions correspond to calculated tip angles of attack higher than those to which the treatment of reference 44 was stated to be applicable. It is shown that the losses due to blade-section stalling are large and that treatments such as that of reference 45 should be used if calculation of power losses is desired for conditions such that stalling occurs in the region of the tip of the retreating blade.

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